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Physique appliquée/*Applied physics*

DU COMBUSTIBLE NUCLÉAIRE AUX DÉCHETS : RECHERCHES ACTUELLES

FROM NUCLEAR FUELS TO WASTE: CURRENT RESEARCH

The characteristics of the Opalinus Clay investigated in the Mont Terri underground rock laboratory in Switzerland

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Note presented by Édouard Brézin.

Abstract In the Mont Terri Rock Laboratory, eleven organisations from six countries (ANDRA and IPSN from France) are investigating jointly a Mesozoic shale formation, the Opalinus Clay. The aims of the research programme are to analyse its hydrogeological, geochemical and rock mechanical properties, the changes induced by the excavation of galleries, by heat-generating waste and by engineered barriers, and to evaluate and improve appropriate investigation techniques. The results of a series of experiments indicate that, at a convenient site, the investigated or similar clay formations could be favourable for hosting a safe repository for radioactive waste. ***To cite this article: M. Thury, C. R. Physique 3 (2002) 923–933.***

rock laboratory / Opalinus Clay / shale / hydrogeology / hydrochemistry / rock mechanics / self-healing

Les proprietés des Argiles à Opalinus étudiées au laboratoire souterrain du Mont Terri en Suisse

Résumé Dans le laboratoire souterrain du Mont Terri, onze organisations de six pays (de France : ANDRA et IPSN) se sont réunies pour étudier les caractéristiques d'une formation argileuse du Mésozoïque, les Argiles à Opalinus. Les objectifs du programme de recherche sont d'analyser leurs propriétés hydrogéologiques, géochimiques et géomécaniques, les changements induits par l'excavation de galeries, par des déchets dégageant de la chaleur et des barrières ouvragées, et d'évaluer et d'améliorer les techniques de recherche appropriées. Les résultats d'une première série d'expériences indiquent que, sur un site favorable, la formation argileuse étudiée et des formations comparables pourrait convenir à accueillir un dépôt de déchets radioactifs. ***Pour citer cet article : M. Thury, C. R. Physique 3 (2002) 923–933.***

laboratoire souterrain / Argiles à Opalinus / argilite / hydrogéologie / hydrochimie / géomécanique / autocicatrisation

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DOSSIER

1. The Mont Terri Rock Laboratory and its research programme

1.1. The initiation of the Mont Terri Project

In 1989, the reconnaissance gallery of the Mont Terri motorway tunnel was constructed and detailed geological and hydrogeological mapping of the Opalinus Clay was jointly carried out by Nagra and the SNHGS (Swiss National Hydrological and Geological Survey). The entire section of the Opalinus Clay revealed itself to be practically impermeable, without any groundwater inflows or damp spots at the tunnel wall. Furthermore, there was no need to place a strong concrete liner as planned. A shotcrete layer was sufficient to stabilise the tunnel wall. It was concluded that the Opalinus Clay might be an interesting host rock for repositories.

Also at this time, in several other countries, the evaluation of argillaceous formations as potential host rock for radioactive waste repositories was started, and in 1991 the NEA (Nuclear Energy Agency) of the OECD created a working group on the Measurement and Physical Understanding of Groundwater Flow through Argillaceous Media – the ‘Clay Club’. In this working group, the possibility of a research programme at Mont Terri was discussed and several ‘Clay Club’ member organisations agreed to start a joint project.

In the autumn of 1994, the SNHGS submitted an application to the *République et Canton du Jura*, the owner of the motorway tunnel, to excavate niches in the Mont Terri reconnaissance gallery and to start an international research programme. Authorisation was granted four months later. An initial research programme and an international co-operation agreement were formulated and agreed, and excavation work began in January 1996.

1.2. Location and layout of the rock laboratory

The rock laboratory is located in northwestern Switzerland, in and beside the reconnaissance gallery of the Mont Terri motorway tunnel. The motorway tunnel was opened to traffic at the end of 1998, and now the reconnaissance gallery serves as an escape and security gallery. Fig. 1 shows the layout of the rock laboratory. It consists of eight niches along the reconnaissance gallery, excavated in 1996 and of a new gallery and several lateral niches, excavated in winter of 1997/98. Fig. 2 shows a photograph of this gallery.

1.3. Organisation of the project

Table 1 lists the organisations involved in the project. The project is run and financed jointly by the eleven project partners and consists of a series of experiments. Each project partner may propose

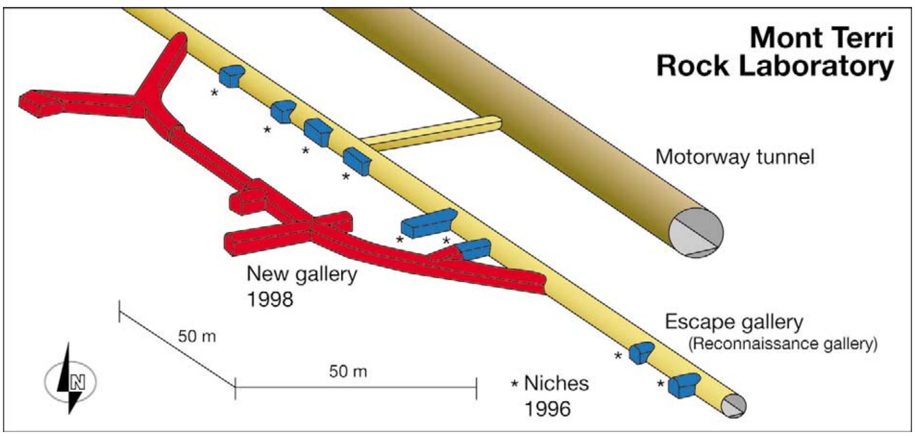

Figure 1. Layout of the Mont Terri rock laboratory.

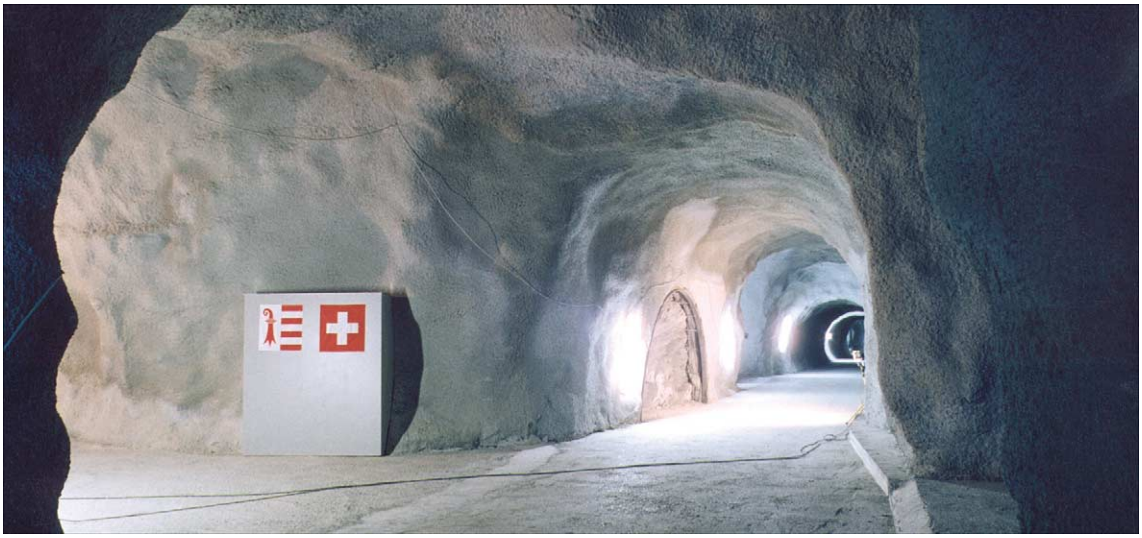

Figure 2. View of the new research gallery system of the Mont Terri rock laboratory. In the foreground left, one of the niches for experiments.

Table 1. Organisations involved in the Mont Terri project

Owner of the motorway tunnel, authorisations		République et Canton du Jura
Project partners		
Switzerland	FOWG/SGS	Federal Office for Water and Geology, Swiss Geological Survey (Direction of the Project)
	NAGRA	National Cooperative for the Disposal of Radioactive Waste
Belgium	SCK•CEN	Studiecentrum voor Kernenergie/Centre d'étude de l'énergie nucléaire
France	ANDRA	Agence nationale pour la gestion des déchets radioactifs
	IPSN	Institut de protection et de sûreté nucléaire
Germany	BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
	GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (GRS)mbH
Japan	JNC	Japan Nuclear Cycle Development Institute
	OBAYASHI	Obayashi Corporation
	CRIEPI	Central Research Institute of Electric Power Industry (from July 2002)
Spain	ENRESA	Empresa Nacional de Residuos Radiactivos, S.A.
Project management		Geotechnical Institute Ltd, St-Ursanne, Switzerland

experiments and decide in which experiments he wishes to participate. Management and financing of the individual experiments is then the responsibility of the participating partners. New project partners are always welcome.

The work is carried out by 32 contracted universities and national research institutes and more than 50 companies from six European countries and Japan. The EC (European Commission) and the Swiss Federal Office for Education and Science financially support four experiments.

1.4. Research programme

The aims of the research programme are to analyse the hydrogeological, geochemical and rock mechanical properties of argillaceous formations and to observe how these properties change during the excavation of galleries, heating of the formation and emplacement of buffer material. As clay formations may react with added water by swelling and disaggregation which may lead to unstable boreholes, an important further aim is therefore to test and improve suitable drilling and investigation equipment and techniques. Table 2 shows the list of aims addressed by the individual experiments of the research programme. At the present time, 31 experiments have been completed and 18 experiments are in progress. The experiments and their results are described in publications and in the series of the Mont Terri Technical Reports, which can be consulted at the offices of the Swiss Geological Survey, SGS (formerly SNHGS).

The results will provide important input for assessing the feasibility and safety of a radioactive waste repository in such a formation. They will also provide interesting data for the disposal of toxic waste and for other research areas such as groundwater exploration, groundwater protection and for petroleum exploration.

2. The characteristics of the Opalinus Clay at Mont Terri

2.1. Rock characteristics

The Mont Terri motorway tunnel crosses the Mont Terri anticline, which is the northernmost anticline of the Jura mountains, formed during the folding of the Jura mountains in the Late Miocene to Pliocene period, about 10 to 2 Million years ago. As shown in Fig. 3, this anticline was sheared off and thrust over

Table 2. Objectives of the research programme, main questions addressed.

Evaluation of appropriate techniques for:
- excavation of conventional and small-diameter galleries, lining, backfilling and sealing
- drilling, coring and overcoring, drilling with liquids, air and gases (e.g., nitrogene)
- in situ water sampling and laboratory water sampling from cores
- hydraulic and gas permeability testing, porewater pressure and stress field measurements

Characterisation of a clay formation (Opalinus Clay):
- What are the mineralogical, structural, mechanical and hydromechanical parameters?
- What is the groundwater composition in faults, joints, undisturbed rock?
- What are typical values and ranges for water/gas permeabilities and gas threshold pressures of faults, joints and undisturbed rock?
- Is osmosis a process which significantly influences the measured hydraulic pressures?
- What are the predominant mechanisms of groundwater flow and solute transport? Advective flow? Stagnant porewater and solute (radionuclide) transport by diffusion?

Changes in the rock induced by excavations, heat and hyperalkaline waters:
- How does the Excavation Disturbed Zone (EDZ) evolve around a gallery (convergence, formation of a fracture system, porewater pressures, hydraulic conductivities, geophysical properties) and what are the parameters?
- How does the unsaturated zone of rock around a gallery (due to ventilation) develop?
- Do fractures in the EDZ seal off when water infiltrates after repository closure? What is the reason for self-healing: swelling of clay minerals, creep?
- What are the thermal characteristics of the Opalinus Clay and what are the effects of heat?
- Can repository generated gas cause fracturing and will such induced fractures seal off (self-healing)?
- What are the hydraulic and geochemical changes in the rock induced by hyperalkaline waters from concrete liners and the waste matrix?

Demonstration of container emplacement and tunnel sealing:
- How can buffer material be emplaced in galleries around waste canisters and what is the interaction between the swelling buffer material and the EDZ in the rock?

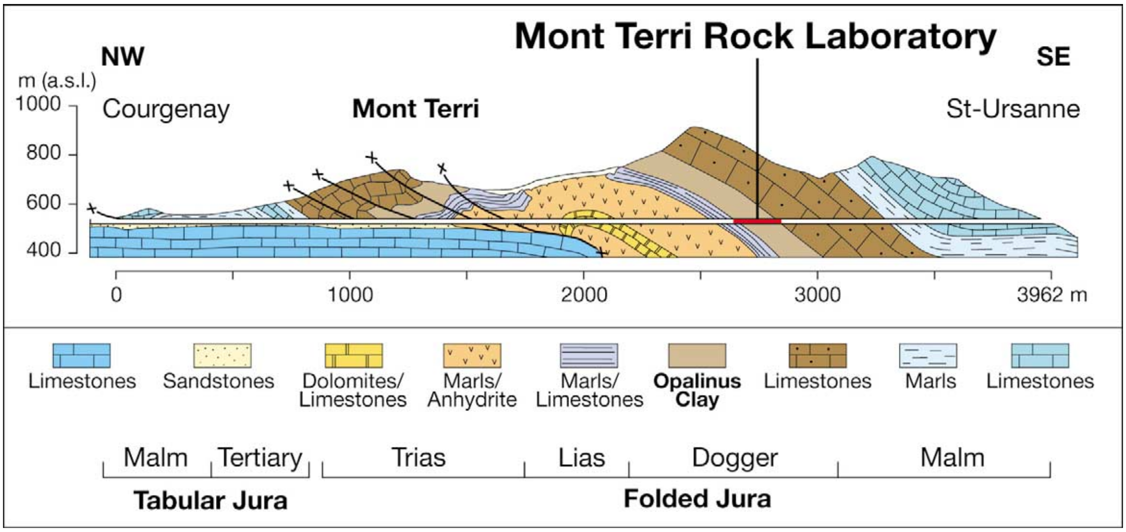

Figure 3. Geological profile along the Mont Terri motorway tunnel [1].

the Tabular Jura of the Ajoie [1]. The present overburden at the rock laboratory site is 250 m to 320 m. The estimated overburden in the past was at least 1000 m.

The Opalinus Clay (Dogger, Lower Aalenian) is a shale formation and was formed as a marine sediment consisting of fine mud particles. It contains between 40 and 80% clay minerals. The reconnaissance gallery intersects a 243 metre-long section of the Opalinus Clay which dips to the Southeast. The thickness is about 160 m. Three slightly different facies can be distinguished: a shaly facies in the lower half of the sequence, a 15 metre-thick sandy-limy facies in the middle of the sequence, and a sandy facies interstratified with the shaly facies in the upper part. Table 3 shows selected key parameters of the predominant shaly facies [2–4].

In the area where the laboratory is located, the rocks are penetrated by several minor faults. One larger fault zone was observed in the centre of the Opalinus Clay in the motorway tunnel, the reconnaissance gallery and the new gallery. This structure is one to several metres thick and is called the 'Main Fault'. This Main Fault is characterised by a large number of fault planes showing slickenslides and shear fibres on a polished surface with a sense of movement that consistently indicates overthrusting. Additionally, the Main Fault contains highly deformed intervals similar to a fault breccia, which show loss of cohesion and a strongly disturbed bedding (drag folds) [2].

2.2. Excavations and lining, drilling techniques

The main part of the new gallery of the rock laboratory was excavated by conventional blasting, creating a horseshoe-shaped profile with a cross-sectional area of 15 m^2. The central part of the new gallery was excavated with a road header, resulting in a 35 metre-long nearly-circular tunnel with a cross sectional area of 11 m^2. Many of the side niches of the new gallery were excavated by a diesel-fuel powered pneumatic hammer excavator. To avoid swelling and to obtain reliable boundary conditions for future experiments, no water was used during excavation. All excavated sections were lined with a 15–20 cm-thick shotcrete layer, reinforced with steel or plastic fibres, as shown in Fig. 2.

A horizontal microtunnel with a diameter of 1.2 m and a length of 40 m, excavated with a modified raise-boring technique, was stable under ventilated conditions without lining, minor rockfall occured in some tectonically disturbed sections only. A short gallery with a diameter of 2.9 m and a length of 15 m, recently

Table 3. Selected key parameters of the Opalinus Clay. Typical values for the shaly facies [2–4].

Parameter		Unity
Clay minerals: Illite, Chlorite, Kaolinite	55	weight%
Clay minerals: IS Illite/Smectite	10	weight%
Quartz (sand, silt)	20	weight%
Calcite (mainly fine shell fragments)	10	weight%
Feldspath, Siderite, Dolomite, Ankerite, Pyrite	5	weight%
Organic carbon	0.2	weight%
Physical porosity (water evaporation at 105 °C)	12–18	vol%
Mercury injection porosity (pores above 4 nm)	5–10	vol%
Hydraulic conductivity	$1{-}5 \times 10^{-13}$	$m \cdot s^{-1}$
Seismic velocity (p-wave)	2100–3700	$m \cdot s^{-1}$
E-modulus perpendicular to bedding	2000–5000	MPa
E-modulus parallel to bedding	5000–15 000	MPa
Swelling heave perpendicular to bedding	7–9	%
Swelling heave parallel to bedding	0.5–1	%
Porewater mineralisation (total dissolved solids)	5000–20 000	$mg \cdot L^{-1}$

excavated with a road header (Engineered Barrier experiment) is stable without lining since created 10 months ago, under ventilated conditions. For safety reasons a plastic net was fixed to protect against small rockfalls.

Drilling technique experiments were carried out to optimise borehole stability and drillcore quality. Drilling fluids with different additives, drilling with compressed air and different drillcore equipment with diameters varying between 36 and 600 mm, were tested. The use of water-based borehole fluids induced swelling and disaggregation of the Opalinus Clay and led to borehole breakouts, rough borehole walls and sometimes to the collapse of boreholes. Drilling with dry, hydrocarbon-free, compressed air resulted in the most stable boreholes, suitable for testing.

2.3. Hydrogeology

The Opalinus Clay has a very low hydraulic conductivity and can be considered to be an aquiclude. The Opalinus Clay is overlain by Middle Jurassic karstic aquifers (e.g., Hauptrogenstein), and underlain by Liassic marls and limestones (e.g., Gryphaea Limestone), with a groundwater circulation in the fracture network of the limestone layers.

In several experiments, the hydraulic conductivity of the Opalinus Clay was measured. A series of in situ packer tests and permeability tests on rock samples were carried out and the results were compared with the conductivities calculated from the long-term water inflow into the water sampling boreholes. The typical values for the hydraulic conductivity parallel to the bedding are $1{-}5 \times 10^{-13}\ m \cdot s^{-1}$ for the shaly and sandy facies and also for the Main Fault [2,4].

The very low hydraulic conductivity and the fact that no water-conducting features or damp spots at the tunnel walls were identified within the Opalinus Clay, led to the conclusion that advective groundwater flow in Opalinus Clay is negligible and that diffusion is the main solute transport mechanism. This is also confirmed by the in situ diffusion experiments in the undisturbed rock and in the Main Fault.

2.4. Hydrochemistry, diffusion

A series of experiments addressed the detailed hydrochemical and isotope-hydrogeological characterisation of the groundwater (porewater) in the Opalinus Clay and a synthesis report is in preparation [3].

Water samples have been collected in situ (natural water inflow into sampling boreholes over months and years) and by squeezing and leaching of rock samples. Analyses of these samples indicate highly mineralised sodium-chloride waters. The water sampled from the Main Fault and the water squeezed from the shaly facies next to the Main Fault have a TDS value of almost 20 $g \cdot L^{-1}$. The Na, Cl and Br contents and the mineralisation of these waters are about half the contents and mineralisation of today's seawater. These highly mineralised water samples were taken in the middle of the approximately 160 metre-thick Opalinus Clay. Towards the adjacent aquifers, the mineralisation and the Cl content of the groundwater decreases. Fig. 4 shows the chloride content of the groundwaters sampled along the reconnaissance gallery. The decreasing Cl content may be explained by diffusion of chloride into the adjacent aquifers with low mineralised groundwater. The chemical composition and isotopic ratios indicate the presence of a significant component of seawater which has probably been in this very low permeability formation for many millions of years.

An experiment for the in situ determination of the diffusion parameters of the Opalinus Clay was carried out [5,6]. Fig. 5 shows the layout of this experiment. A test section was packed off and, after reaching porewater pressure equilibrium, tritium- and iodide-traced water was circulated, allowing diffusion of these tracers into the rock of the test section. After one year of circulation, the test section was overcored (Fig. 5) and the tritium and iodide concentrations were analysed in several series of samples. For tritium, the calculated effective diffusion coefficient D_e parallel to the stratification was 5×10^{-11} $m^2 \cdot s^{-1}$, which is comparable with the diffusion coefficient derived from a few laboratory experiments on rock samples parallel to the stratification. From a series of laboratory experiments it can be derived that the diffusion coefficient perpendicular to the stratification is about 5 times smaller than parallel to it.

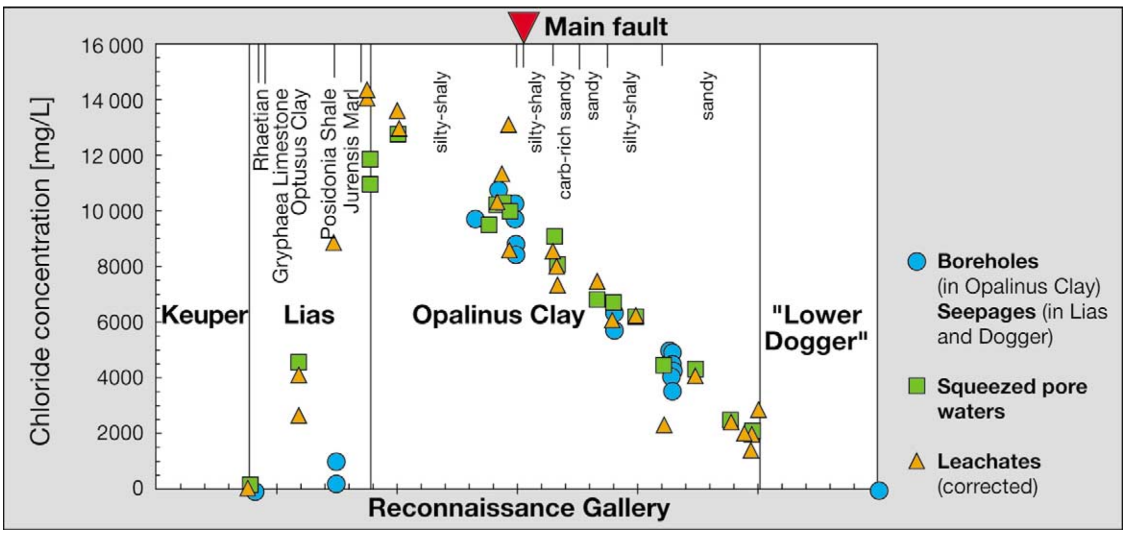

Figure 4. Chloride concentration in Opalinus Clay pore water and adjacent formations along the reconnaissance gallery [3].

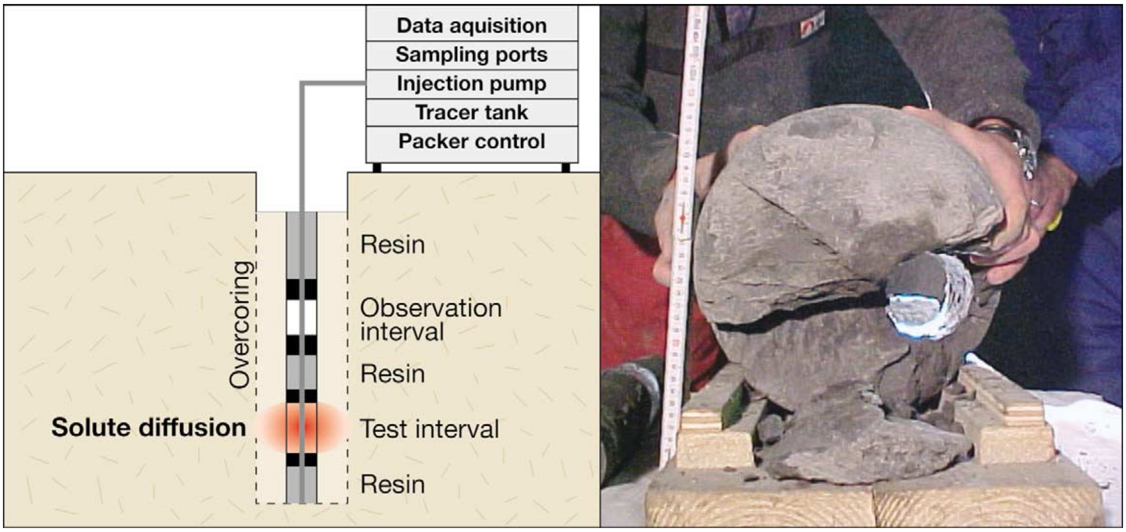

Figure 5. Layout of the Diffusion Experiment [5] and core of the test zone, overcored after 1 year of diffusion of HTO.

3. The modifications of the Opalinus Clay induced by excavations

3.1. The Excavation Disturbed Zone (EDZ)

During and after excavation of a tunnel, the rock expands into the cavity, resulting in the formation of an excavation disturbed zone (EDZ), and – depending on the rock strength and the stress situation – of a fracture system. When the niches were excavated in the reconnaissance gallery in 1996, numerous open unloading fractures were observed in the rock behind the tunnel wall at the intersection with the niches. These fractures often ran parallel to the wall of the reconnaissance gallery [2,7,8]. In an experiment resin was injected under slight overpressure into a borehole in the gallery wall. The borehole was then overcored with a larger diameter and further boreholes were drilled in the vicinity. Resin-filled joints were observed in the drillcores to depths of about 80 cm from the tunnel wall. This indicated that the open fractures were at least partly interconnected.

The hydraulic characterisation of the EDZ was investigated in various packer-tests. Test interpretations indicate that the local hydraulic conductivity may be several orders of magnitude higher in the first 50 cm of the EDZ, and one or two orders of magnitude higher in the less-disturbed rock in the zone between 50 cm and 3 m from the tunnel wall, compared to the hydraulic conductivity of the undisturbed rock [9].

3.2. Swelling and disaggregation of Opalinus Clay

In contact with water, decompressed Opalinus Clay swells and under confined conditions, the swelling process is associated with an increase in pressure. Swelling tests were carried out with various water types (deionised water, low mineralised water, synthetic porewater and KCl solution). For samples of the shaly facies, the maximum measured swelling heave perpendicular to bedding is 9% and is up to 10 times greater than that parallel to bedding. This value was obtained with deionised water. Higher mineralised waters result in smaller swelling heaves by a factor of up to 2 only.

The excavated Opalinus Clay was recently deposited in the open air and exposed to rainfall and weathering. After a few months the blocks swelled and disaggregated at the block surface into millimetre-thick sheets of a few millimetres size, as shown on Fig. 6. In the central parts of the blocks the rock was brittle, could be cut with a knife and crushed with the fingers. The porosity rose from initially 12–18 vol%

Figure 6. Opalinus Clay exposed to weathering, expanded and disaggregated.

to about 28 vol%. After a year, some blocks were disaggregated in their outer zone into a paste rich in sheets of not yet completely disaggregated clay, with a porosity of 30–42 vol%. In the centre of the blocks, still undisaggregated but swollen parts with a porosity of 25–29 vol% were found. These observations nicely demonstrate the very strong and fast reaction of the decompressed Opalinus Clay with water, resulting in swelling and disaggregation.

3.3. Self-healing of the EDZ

The interconnected open fracture system in the EDZ may represent a pathway for advective-dispersive flow and radionuclide transport. However, observations and first results of experiments at Mont Terri indicate that self-healing may close this interconnected open fracture system by the above described swelling process.

Due to an unsuccessful manipulation in horizontal boreholes, water infiltrated into the open fractures in the EDZ of a niche in the reconnaissance gallery. This water led to swelling, disaggregation and creep of the Opalinus Clay. As shown on Fig. 7, the shotcrete could not resist and tore. The maximum movement of the broken shotcrete plates after three years is 20 cm and still continues. The rock directly behind these shotcrete plates is damp and brittle. A rock sample had a high porosity of 27 vol% and a water saturation of the pores of about 75%.

In an experiment, a series of boreholes was drilled into the EDZ. With pneumatic and hydraulic packer tests over distances of up to one metre the interconnectedness and the high hydraulic conductivity of the EDZ fracture system was demonstrated [10]. The injected water reacted with the rock and periodically-repeated hydraulic tests showed a decrease of the transmissivity of the fractures by a factor of about 50 after one year, a clear indication of the start of a self-healing process.

For an assumed waste-containing disposal gallery, backfilled and sealed with swelling bentonite, the EDZ self-healing process may be characterised by the following steps:

(a) infiltration of water into the interconnected open fracture system of the EDZ;
(b) reaction of this water with the Opalinus Clay at the fracture surfaces, start of swelling and disaggregation of the clay and closing of the open fractures;
(c) creep of the blocks which contain an outer rim of swelled and disaggregated clay, and convergence of the tunnel until stabilisation by the swelling bentonite in the disposal gallery.

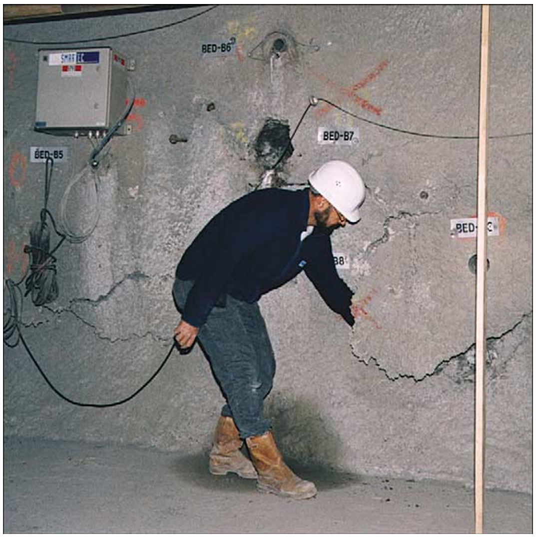

Figure 7. Shotcrete displacements caused by swelling and disaggregation of Opalinus Clay.

The EDZ then contains along the healed fractures a network of swollen disaggregated Opalinus Clay with enhanced porosity, resulting in probably slightly enhanced hydraulic conductivity and diffusion.

4. Conclusions

In the Mont Terri Rock Laboratory an international research programme has been in progress since 1996. At present time, 31 experiments have been completed and 18 experiments are running. The results have allowed the characterisation of the Opalinus Clay and the development of a conceptual understanding of the various processes occurring in this and in similar formations.

The excavation of galleries was well feasible and galleries of 4 to 5 m diameter are stable with a shotcrete lining. A recently excavated short gallery with a diameter of 2.9 m has been stable for 10 months without lining.

The Opalinus Clay at Mont Terri is of very low permeability and no discrete water inflows or damp patches have been observed in the rock laboratory, not even in a major tectonic fault. No significant advective groundwater flow is expected and the porewater in the clay is practically stagnant. Radionuclides potentially released from a repository in Opalinus Clay can be transported through the clay virtually by diffusion only.

During the excavation of galleries, a partly interconnected open fracture system was formed behind the tunnel walls, which could allow advective groundwater flow and radionuclide transport. However, in contact with water, swelling and disaggregation of the clay seems to lead to efficient self-healing of this fracture system.

The current indication is that the investigated and similar formations could be favourable for hosting a safe repository for radioactive waste (Mont Terri is located in a tectonically complex situation and is excluded as a repository site).

It is planned to carry out long-term experiments to confirm and improve the actual process understanding and the conceptual models, for instance on radionuclide diffusion and on self-healing of fractures.

The future evolution and the progress of the Mont Terri Project may be consulted at **www.mont-terri.ch**.

Acknowledgements. The author, who initiated and directed the Mont Terri Project, would like to thank Charles Emmenegger of SNHGS and André Voutat, Alain Waldmeyer, Jacques Babey, Minister Pierre Kohler and Minister Jean-François Roth of the *République et Canton du Jura*. Without their personal support, it would not have been possible to create this project.

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Discussion

Question de C. Devillers

Quelle extension de l'EDZ avez-vous observé au Mont Terri ? Comment dépend-elle des dimensions des galeries ?

Réponse de M. Thury

Dans la galerie de reconnaissance du Mont Terri d'un diamètre de 5 m, l'EDZ se manifeste en fissures parallèles aux parois jusqu'à une distance de 2 m. La fréquence des fissures est haute dans le premier mètre (5–30 m^{-1}), les fissures sont interconnectés. Dans les premiers 60–80 cm on observe des cristaux de gypse sur les surfaces des fissures. Plus loin la fréquence des fissures diminue avec la distance de la paroi.

Dans une galerie d'un diamètre de 3 m, une zone de fissures interconnectés d'une épaisseur de également 1 m environ à été observée.